P.D. 16-06-2000
P. 65-69

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# Umformen und Kühlen von direktgegossenem Stahlband

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*In-line rolling and cooling of direct cast steel strip*

Das Dünnbandgießen nach dem Zweirollenverfahren wird von verschiedenen Konzernen und Forschungsgruppen als Verfahren zur Warmbanderzeugung weiterentwickelt. Die Umsetzung in die betriebliche Produktion sowie die Vermarktungsphase haben begonnen. Die Potentiale dieses Gießverfahrens liegen neben der raschen Erstarrung und der geringen Banddicke auch bei den Möglichkeiten der In-line-Bandbeeinflussung zwischen Gießmaschine und Haspel. Gute Festigkeits- und Dehnwerte des Warmbandes werden bei vielen Stählen bereits im Gußzustand oder nach einer Anlaßglühung erreicht, wenn die Temperaturführung des Bandes auf die Stahlsorten im Hinblick auf die Gefügeumwandlungen abgestimmt wird. Weiteres metallurgisches Potential ergibt sich – bei erweiterter Anlagentechnik – durch den Einsatz der In-line-Warmumformung des gegossenen Dünnbandes. Untersuchungen hierzu wurden von der Thyssen Krupp Stahl AG und dem IBF der RWTH Aachen mit folgenden Ergebnissen durchgeführt: Unerwünschte, harte Gefügephasen konnten unterdrückt, die Korngröße verringert, Mikroporen geschlossen werden. Warmband mit geringen Dicken ließ sich so erzeugen.

Die Übertragbarkeit der Forschungsergebnisse auf industrielle Bandgießanlagen ist gegeben, wobei die Wege Bandgieß- und Laborversuche sowie numerische Simulation für die Werkstoff- und Verfahrensentwicklungen zur Verfügung stehen.

Twin roll strip casting is being under development as a process for alternative hot strip production. Now, the marketing and the commercial production phases have been started. Rapid solidification, low hot strip thickness and the chances of in-line-treatment between caster and coiler all contribute to the potential of this casting process.

For several steel grades good mechanical strip properties will already be obtained in the as-cast state or after an annealing process if the cooling cycle of the strip is adjusted to the steel grade, as far as the phase transformation behaviour is concerned. Another metallurgical potential is brought about by incorporating an in-line hot rolling step. Investigations in this field carried out by Thyssen Krupp Stahl AG and the Institute for Metal Forming (IBF) of RWTH Aachen led to the following results: unwanted hard microstructure phases are avoided, grain diameter is decreased, micropores are closed and low final strip thickness is achieved.

The transferability of the research results to industrial strip casting facilities is given, and the routes of strip casting, laboratory experiments and numerical simulation methods are ready for further development of both the material and process.

Vorgetragen auf der Jahresveranstaltung „Stahl '99" am 11. November 1999 in Düsseldorf.

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In Versuchsreihen wurde gezeigt, daß ein gegossenes Band aus Kohlenstoffstahl mit Massengehalten von 0,7 % Kohlenstoff ohne jegliche Glühungen auf 0,5 mm kaltgewalzt werden kann [13]. Die ersten Stiche beim Kaltwalzen treffen auf einen weichen Werkstoff, wie rekristallisiertes, entfestigtes Warmband.

Geglühte Kaltbandproben konnten in einem betrieblichen Prozeß weiterverarbeitet werden, wie das Beispiel einer Pkw-Türschloßleiste zeigt, **Bild 3.** Die Grundvoraussetzung hierfür ist allerdings eine optimierte Temperaturführung zwischen Gießmaschine und Haspel, um die Perlitumwandlung für die gewünschte Kaltumformbarkeit bei gleichzeitig hoher Festigkeit zu steuern.

Die Herstellung von längsnahtgeschweißten Rohren aus bandgegossenen, weichen *Kohlenstoffstählen* nach dem Kaltwalzen und anschließendem Feuerverzinken ist möglich [4].

Über die Weiterverarbeitbarkeit eines Gußbandes aus *nichtrostenden austenitischen Stählen* ist vielfach berichtet worden. Zur betrieblichen Kaltbanderzeugung steht die Prozeßroute Bandgießen-Glühbeizen-Kaltwalzen zur Verfügung. Das Halbzeug eignet sich z. B. für Haushaltswaren oder Rohre [13].

Versuche zum Kaltwalzen von *höherfesten mikrolegierten Stählen* ergaben nach normalisierendem Glühen mechanisch-technologische Endeigenschaften, die die Anforderungen an Kaltband dieser Sorte erfüllten [13].

Die Untersuchungen zeigten auch, daß in einigen Fällen mit Streuungen der *Dehnwerte* des Kaltbandes zu rechnen ist [14]. Dies scheint zwei Ursachen zu haben: Einerseits können unerwünschte, harte Sekundärphasen im Gefüge dafür verantwortlich sein; andererseits kann es an Resten erstarrungsbedingter Mikroporen in der Bandmittenzone liegen.

Besonders *Stahlsorten mit breitem Erstarrungsintervall* – wie hochkohlenstoffhaltiger Stahl – neigen zu Mikroporen, wenn der Bandkern ein globulitisches Gefüge aufweist. In hochlegierten Chrom-Nickel-Stählen liegt die Porengröße im Gußzustand stets wesentlich niedriger als bei unlegiertem Kohlenstoffstahl. Ein Warmumformstich verschließt die Poren. Auch nach Kaltwalzen mit mehr als 60 % bezogener Höhenabnahme und anschließendem Schlußglühen sind keine Poren mehr feststellbar [14].

**Potentiale.** Die Bandgießtechnologie bietet mit den Möglichkeiten der *thermomechanischen Behandlung* interessante Potentiale, um die problemlose Verarbeitbarkeit von Stahlbändern sicherzustellen und auf weitere Stahlsorten auszudehnen. Durch die im Vergleich zum Warmwalzen niedrige Transportgeschwindigkeit bieten sich Möglichkeiten zur Gefügebeeinflussung durch Kühlung bei sehr unterschiedlichen Temperaturführungen an, **Bild 4.** Die Bandkühlung kann direkt unterhalb der Gießrollen einsetzen, wo das gegossene Band eine Temperatur von über 1250 °C besitzt. Die exakte Einstellung von Haspeltemperaturen bis unterhalb von 100 °C ist ebenfalls problemlos möglich. Das dünne Warmband kann mit hoher Intensität bis zum Bandkern gekühlt werden. Damit lassen sich beispielsweise Korn- und Zunderwachstum einschränken als auch die Phasenumwandlungen steuern.

Eine weitere Möglichkeit zur Beeinflussung der Bandeigenschaften ist die *In-line-Warmumformung.* Hierdurch können unter Berücksichtigung der Temperaturführung zusätzliche Gefügeeinstellungen vorgenommen werden, z. B. durch Rekristallisation oder Erholung. Besonders für Stahlsorten, die während der Abkühlung zur Bildung von unerwünschten, schwer umformbaren Gefügebestandteilen, wie Bainit und Martensit, neigen, ist dies eine geeignete Maßnahme zur Verbesserung des Kaltumformvermögens. Entsprechende Versuche sind auch von anderen Anlagen bekannt [4; 16...19]. Weitere Versuche zur Erforschung latenter Potentiale werden von der Thyssen Krupp Stahl AG und dem IBF durchgeführt. Dabei kommt auch die numerische Simulation der In-line-Warmumformung zum Einsatz. Die Pilot-Bandgießanlage wurde hierfür umgebaut und erweitert, so daß auf wassergekühlten, vernickelten Kupferrollen mit 580 mm Durchmesser ein 150 mm breites Band in Dicken von 0,8 bis 3,0 mm vergossen werden kann. In einer zusätzlichen Kühlzone wird das Band direkt unterhalb des engsten Gießrollenspaltes mit Wasser abgeschreckt, **Bild 5.** Abkühlungsgeschwindigkeiten

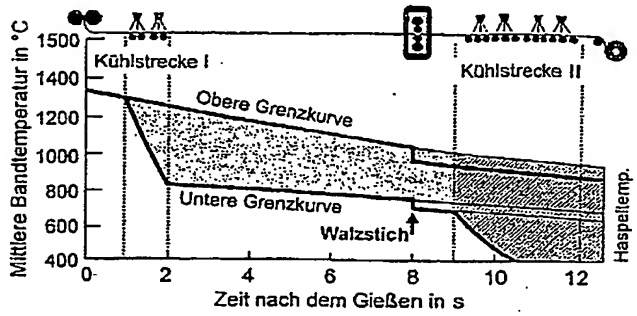


**Bild 4.** Möglichkeiten zur thermomechanischen Behandlung von gegossenen Bändern

**Fig. 4.** Possibilities of in-line thermo-mechanical treatment of as-cast steel strip

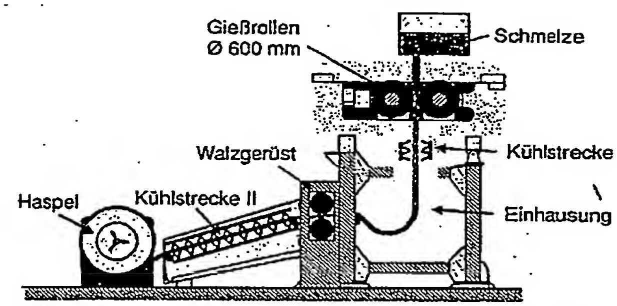


**Bild 5.** Pilot-Bandgießanlage am Institut für Bildsame Formgebung, RWTH Aachen

**Fig. 5.** Pilot-scale twin roll caster at the Institute for Metal Forming, RWTH Aachen

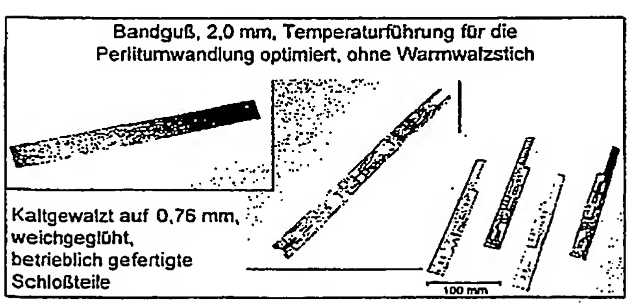


**Bild 3.** Schloßleisten, hergestellt aus gegossenem Dünnband

**Fig. 3.** Lock plates manufactured from a cast strip

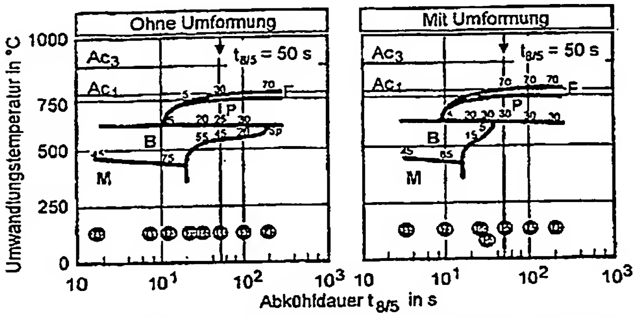


**Bild 9.** Veränderung der Gefügezusammensetzung eines perlitarmen höherfesten Stahls durch In-line-Warmumformung; Simulation im Umformdilatometer

**Fig. 9.** Influence of hot deformation on the microstructural phases of a pearlite reduced high-strength steel after simulation using a hot forming dilatometer

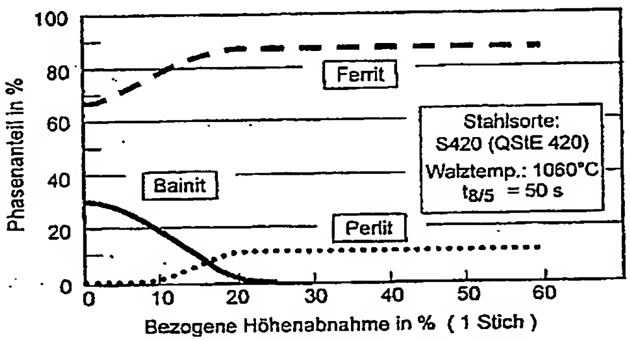


**Bild 10.** Ergebnisse einer numerischen Simulation des In-line-Warmwalzens von Gußband

**Fig. 10.** Results of a numerical simulation of in-line hot rolling of an as-cast steel strip

weils einem Stich für den Stahl ähnlich der Sorte S420 (QStE 420) berechnet. Ab einer Höhenabnahme von 20 % wird unerwünschter Bainit vermieden, **Bild 10.**

Beim *mikrolegierten Baustahl* ergibt die Berechnung der Ferritkorngröße von Gußband im Vergleich zu in-line-gewalztem Band ein um etwa eine Klasse feineres Korn. Ersetzt man die 1-Stich-In-line-Umformung von 50 % durch zwei Stiche mit gleicher bezogener Gesamthöhenabnahme, wird aufgrund einer zusätzlichen Rekristallisation eine weitere Ferritkornfeinung um 1 1/2 Klassen erwartet. Möglichkeiten zur Gefügeoptimierung ergeben sich durch Variation der Stichabnahme, der Pausenzeiten zwischen den Stichen und der Temperaturführung.

Innerhalb der Simulation wurden die Verhältnisse der Pilotanlage (180 mm Walzendurchmesser, 33 m/min Gießgeschwindigkeit) auf eine gedachte Betriebsanlage (600 mm Walzendurchmesser, 60 m/min Gießgeschwindigkeit) bei gleicher bezogener Höhenabnahme hochgerechnet. Durch die Vergrößerung des Walzendurchmessers und Erhöhung der Gießgeschwindigkeit werden die Gefügebestandteile und die geringen Korngrößen für den mikrolegierten Baustahl ebenso erzielt. Trotz Vergrößerung der gedrückten Länge bleiben sowohl Berührzeit als auch Umformgeschwindigkeit etwa gleich.

Beispielsweise können durch das In-line-Walzen eines 1,5 mm dicken Gußbandes in einem Stich ultradünne Warmbänder von ≤ 0,75 mm Dicke erzeugt werden. Dies ist besonders für höherfeste Stahlsorten interessant, die während des Warmwalzens in einer Warmbreitbandstraße stark verfestigen und deren Umformwiderstand dann beim Walzen auf sehr geringe Enddicken entsprechend stark ansteigt.

## Danksagung

Die Autoren danken dem Land Nordrhein-Westfalen und der EGKS für die Unterstützung von Projekten, in denen Ergebnisse der experimentellen und numerischen Simulation erarbeitet werden konnten. (S 30325)

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Translation of article from *Stahl und Eisen, Vol. 120, No.6 (June 2000)*

# Forming and cooling of direct cast steel strip

by

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## Thin strip casting technology

By virtue of the development of new production methods for hot-rolled strips with dimensions which are close to the final ones, the part-processes of casting/solidification and hot rolling are brought closer together. Examples of such combined processes are thin slab casting with integrated hot-rolling train, rough strip casting with belt caster and direct thin strip casting using the twin roll method. In the following the state of the development and further possibilities of hot rolled strip production are illustrated by the short production line of thin strip casting, Fig.1, and discussed.

When casting thin strips with twin roll caster, the steel smelt solidifies into a strip immediately on both casting rollers. The achievable strip thicknesses are between 1-6 mm; strips below 1 mm thickness can be also directly cast. A secondary cooling zone is missing, so that in addition to the overheating almost the entire heat of the solidification is eliminated via the casting rolls. The capacity of a single-strand twin roll strip casting plant for the hot strip production can be approx. 350,000-550,000 t/year, depending from the width, construction of the plant and casting program.

In contrast to the cast-rolling technology, that has been employed for 10 years in industrial production /1;2/, the thin strip casting technology is at this stage only at the threshold of industrial use.

## Strip casting plants

Industrial-scale plants for twin roll casting are operated by NSC in Japan /3/ and BHP in Australia /4/, Table 1. The industrial plants have already proven their capability to produce strips from austenitic stainless steels and carbon steels, e.g. 5-hour casting period and sequential casting in the Myosotis project /5/. Posco operates in Korea a large-scale pilot plant /6/. Nucor, IHI and BHP intend to commence a joint venture for the production of hot rolled strips in the USA /7/. Commercial plants for industrial-scale strip casting of carbon steel are already being offered by manufacturers of these plants

/4/. A pre-industrial twin roll strip casting plant for stainless steels is being built and will be operated by Krupp Thyssen Nirosta in Krefeld within the European cooperation Eurostrip between Thyssen Krupp Steel, Voest Alpine Industrieanlagebau GmbH and Usinor /8;9/.

Laboratory-scale and small pilot plants serve the purpose of testing the castability of strips and the further development of other types of steels. They include high silicon electrical strip or the investigation of solutions of technical details. The latter are researched within the Thyssen Krupp steel group on two pilot plants: one plant operates on industrial scale at AST in Terni /10/, the other at the Institut für Bildsame Formgebung *[IBF = Institute for ductile shaping]* of the RWTH *[Technical University of Rhine Westphalia]* Aachen /11/. The DSC *[direct strip casting]* or single belt casting methods are also being further developed in pilot and laboratory plants /12/.

**Properties of directly cast strips**

The through-solidification times of approx. 0.5 sec occurring during strip casting are very short when compared with continuous slab or continuous thin slab casting, but also with DSC rough strip casting, Fig.2. As a result of this short solidification times an advantageously fine casting structure is obtained with comparatively small segregation. This leads to the conclusion that, inter alia, the influence of the trace elements on the castability is reduced. This can result in advantages for the process like, for example, an increased allowable scrap content for the steel production.

*Further processing.* Numerous investigations of the properties of the materials of directly cast strip have shown, that this material is well suited for cold rolling. The fine casting structure does not present any obstacle for an effective forming /13/. Appropriate steps during casting make it also possible to set the required thickness profile of the hot-rolled strip /4...6/.

A series of investigations has shown, that a cast strip from carbon steel with a 0.7% carbon contents can be cold rolled to 0.5 mm without any annealing /13/. The first passes during cold rolling impact on a soft material, like a recrystallised, softened hot rolled strip.

Annealed cold-rolled strip specimens could be further processed in an industrial process, as is shown on the example of a door lock strip of a motor vehicle, Fig.3. The basic prerequisite for this is, however, an optimised temperature management between the casting machine and the coiler, to enable to control the transformation of the perlite for the desired cold formability with a simultaneously high strength.

The manufacture of pipes with longitudinal welding seams from strip-cast, soft carbon steels following cold rolling and subsequent hot galvanizing is possible /4/.

Many reports have been written about the possibility to further treat a cast strip made from stainless austenitic steels. For an industrial cold-rolled strip production the strip casting/anneal heating/cold rolling process route is available. The semi-product is suitable, for example, for household products or pipes /13/.

Experiments to cold roll high-strength micro-alloyed steels after normalising annealing resulted in final mechanical-technological properties which satisfy the demands placed on cold-rolled strip of this type /13/.

The investigations have also shown, that in some cases one has to expect a distribution of the elongation values of the cold-rolled strip /14/. This seems to have two reasons: on the one hand undesirable, hard secondary phases in the texture may be responsible for this; on the other hand it may be due to the residues of solidification-induced micropores in the central zone of the strip.

In particular steel types with a broad solidification range, like steel with high carbon content, have a tendency for micropores when the core of the strip has a globular texture. The size of the pores in highly alloyed chromium/nickel steels in the cast state is always considerably smaller than in the case of an unalloyed carbon steel. A hot forming pass closes the pores. Even after cold rolling with more than 60% of height reduction and subsequent final annealing no pores can be established /14/.

**Potentials**

With the possibility of thermo-mechanical treatment the strip casting technology offers interesting potentials to ensure a problem-free processing of steel strips and extend it to

further steel types. By virtue of the low transport velocities, when compared with hot rolling, there are possibilities to influence the texture by cooling using very different temperature managements, Fig.4. The cooling of the strip can take place directly below the casting rollers, where the cast strip has a temperature of above 1250 C°. The accurate setting of the coil temperatures to below 100 C° is also possible without any problem. The thin hot-rolled strip can be cooled with great intensity up to the core of the strip. Thus the growth of the grain and scale, for example, can be limited, as well as the phase transformations.

A further possibility to influence the properties of the strip is the in-line-hot forming. Taking into consideration the temperature management, by virtue of this additional textures can be achieved, e.g. by recrystallisation or recovery. This is a suitable measure for the improvement of the cold forming capability particularly for those types of steel which are inclined to form during the cooling undesirable, difficult to form texture components, like bainite and martensite. Corresponding experiments in other plants are also known /4; 16...19/. Further experiments researching possible potentials have been carried out by Thyssen Krupp Stahl AG and IBF. Numerical simulation of the in-line hot forming is also used in this case. The pilot strip casting plant was reconstructed for this purpose and extended, so that a 150 mm wide strip with thicknesses between 0,8 and 3.0 mm can be cast on water-cooled, nickel-plated copper rollers with a 580 mm diameter. The strip is chilled with water in an additional cooling zone directly below the narrowest gap between the casting rollers, Fig.5. Cooling rates of approx. 300 K/sec are realised on this occasion. The oxygen content of the atmosphere can be greatly reduced within the enclosed region. A rolling stand is arranged in series. If required, the temperature of the coil is adjusted in a second cooling zone.

**Consequences regarding the texture**

In the case of micro-alloyed construction steels and high silicon steels a clear reduction of undesirable, hard texture components have been established while simultaneously refining the grain by in-line hot rolling. A perlite-poor high-strength steel, similar to the type S420 (QStE 420), in a slowly cooled state has a cast texture of ferrite as well as of 15% bainite, Fig.6. The in-line-hot forming with approx. 30% height reduction approx. 5 sec after the through-solidification results in a fine-grained, bainite-free ferrite-perlite

texture, that can be directly cold formed. Further annealing to dissolve the bainite becomes therefore superfluous.

The grain refining affect of a hot rolling pass brings the fine texture, already in the casting state, to a level of conventionally produced hot-rolled strips. The ferrite grains are present in the cast strip with a diameter between 6.5 and 10 µm ($G_{ASTM}$= 10.3-11.5), after an in-line-forming ferrite grains with only 3.6 to 5.0 µm ($G_{ASTM}$= 12.3-13.2) have been detected.

Due to its carbon contents of approx. 0.08% a cast strip from high silicon steel for grain-oriented electrical strips has in the cooled state often needle-like perlite and martensite on the edges of large ferrite grains, Fig.7. The ferrite grains are stretched by a 50% in-line hot forming. Originally austenitic grain regions, which surround the ferrite grains, transform into ferritic-perlite ones. Due to this these types of steels have a better capability to be formed cold /20/.

**In-line rolling**

*Simulation of in-line hot rolling.* The transformation behaviour of strip cast, high strength, perlite-poor steel were established experiments by using a dilatometer. On this occasion, for the purpose of comparison, the work was carried out with and without a simulated forming step. The austenite texture in the cast state was post-detected in the forming dilatometer by a 10 min austenisation at 1250 C°. To establish a time/temperature transformation diagram, specimens with different $t_{8/5}$ times were cooled. When recording the transformation[?]/time/temperature transformation diagram, after austenisation an additional forming of 50% height reduction was carried out at 1050 C°.

The ferrite and perlite regions were shifted only a little for short periods; the bainite region, however, was constricted to great extent, since the ferrite-perlite transformation was induced by the transformation, Fig.8.

The texture for a $t_{8/5}$ time of 50 sec, set in the transform dilatometer is illustrated, in the non-transformed and transformed state in Fig.9. The texture of ferrite, perlite and up to 45% of bainite is transferred into a purely ferritic-perlitic texture at the same cooling rate.

With the aid of numerical simulation, based on model calculations, the thermo-mechanical processes during strip casting are optimised with a rolling stage, as this is nowadays conventional in the case of hot rolling /21/. The object is studies of parameters to narrow down the technological window for targeted experiments and the portability of transfer the results obtained on laboratory scales to plants for industrial production. The model alignment is carried out by dilatometer experiments with parameters close to industrial ones.

As an example, the influence of the degree of hot forming with related height reduction between 10% and 60% were calculated for one pass each for a steel, similar to the S420 (QStE 420) type. From a height reduction of 20% on, the undesirable bainite is avoided, Fig.10.

In the case of a micro-alloyed construction steel the calculation of the size of the ferrite grain of a cast strip results in a grain, that is approximately one class finer than that of a strip rolled in-line. If the one-pass in-line-forming of 50% is replaced by two passes with the same total height reduction, due to an additional recrystallisation a further refining of the ferrite grains by 1 ½ classes is expected. The possibilities of optimising the texture are obtained by varying the reduction per pass, the times between the passes and the temperature management.

The ratios of the pilot plant (diameter or roller 180 mm, casting rate 33 m/min) were extrapolated within the scope of the simulation to apply to an assumed industrial plant (diameter of roller 600 mm, casting rate 60 m/min), with the same height reduction. By increasing the diameter of the rollers and increasing the casting rate, the components of the texture and the small grain sizes for the micro-alloyed steel were also achieved. Despite the increase of the compressed length both the contact time and the forming speed remained almost the same.

In form of an example, by in-line rolling a 1.5 mm thick cast strip ultra-thin hot-rolled strips of ≤0.75 mm thickness can be produced in one pass. This is of particular interest for high-strength steel types, that during the hot rolling in a hot-rolled wide strip train harden greatly and their resistance to forming increases correspondingly to great extent when being rolled to very thin final thicknesses.

### Acknowledgment

The authors express their thanks to the State of North Rhine-Westphalia and EGKS *[European Coal and Steel Association]* for their support of projects, in which the results of experimental and numerical simulation could be acquired.

### Bibliography

Not translated

## Table and figures

Table 1

| | | | |
|---|---|---|---|
| Twin roll caster | | | |
| Industrial plants | Japan | NSC/MHI | stainless steels |
| | Australia | BHP/IHI | soft carbon steels |
| | Italy | AST | stainless steels, carbon steels and silicon steels |
| | France | Usinor/TKS* | " |
| | Korea | Posco | stainless steels and others |
| | Germany | KTN** | stainless steels |
| Pilot and laboratory plants | France | Irsid | alloyed and non-alloyed steels |
| | Germany | MPI | " |
| | Germany | TKSI/IBF | " |
| | UK | Corus | " |
| | Canada | IMI* | " |
| Belt caster | | | |
| Pilot and laboratory plants | Germany | TU Clausthal | carbon steels |
| | Sweden | Mefos | " |
| | Canada | McGill | " |

*) no experimentations at this stage **) Under construction and starting up

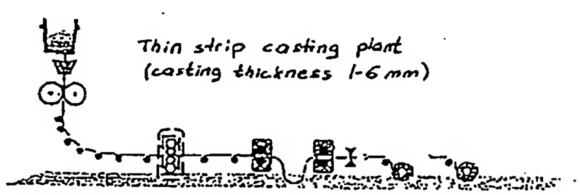


Fig. 1. Principle sketch of a twin roll caster facility

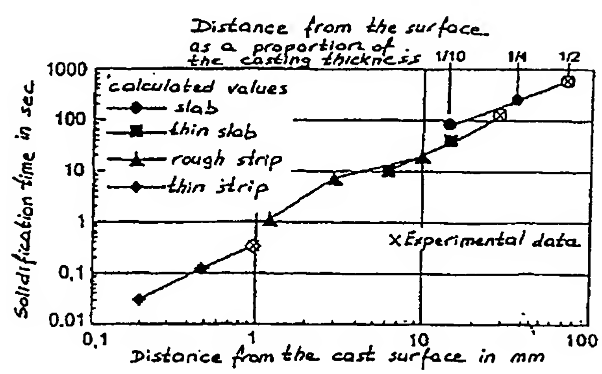


Fig. 2. Solidification time vs. distance from the surface of a slab or strip

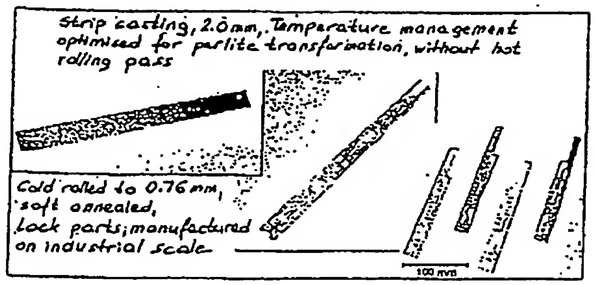


Fig. 3. Lock plates manufactured from a cast strip

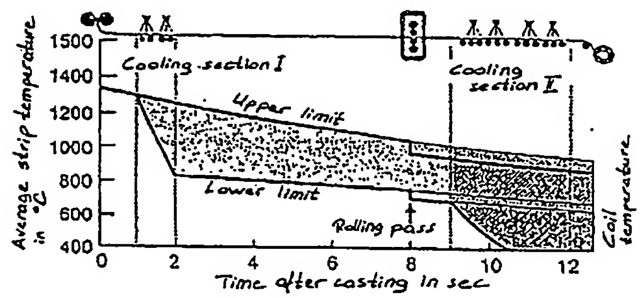


Fig. 4. Possibilities of in-line thermo-mechanical treatment of as-cast steel strip

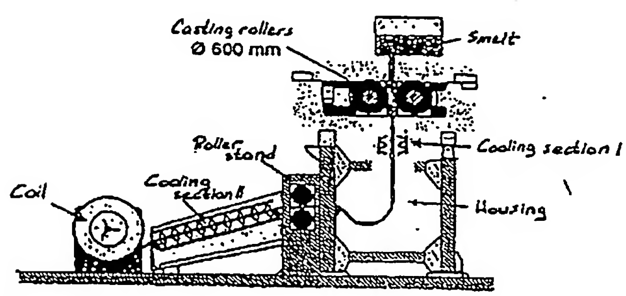


Fig. 5. Pilot-scale twin roll caster at the Institute for Metal Forming, RWTH Aachen

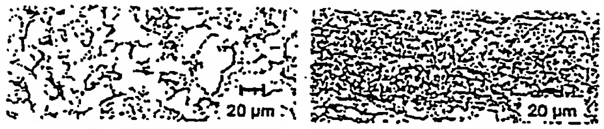


Fig. 6. Microstructure of a pearlite reduced high strength direct cast hot strip
left: after cooling, 1.2 mm strip thickness, right: after in-line hot rolling and cooling, $\varepsilon_h = 30\%$

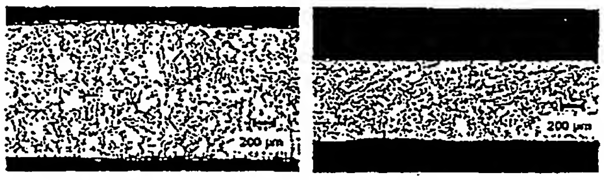


Fig. 7. Microstructure of a high silicon alloyed direct cast hot strip
left: as-cast; martensite and acicular pearlite on the grain boundaries, longitudinal section, 1.4 mm strip thickness; right: in-line hot rolled cast strip; ferrite grains trimmed by pearlite, longitudinal section, 0.85 mm strip thickness


Fig. 8. Effect of in-line hot rolling on the transformation behaviour of a pearlite reduced high-strength directly cast hot strip microstructure without (left) and with (right) deformation simulated in a hot forming dilatometer, $\varepsilon_h = 50\ \%$, $t_{8/5} = 50$ s

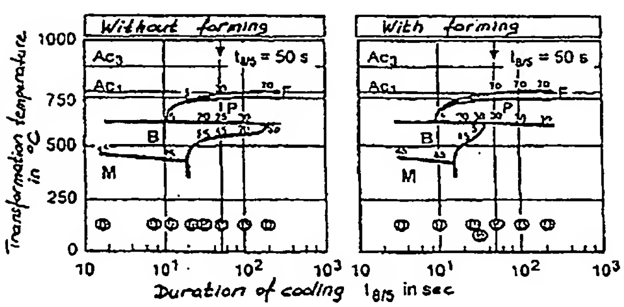


Fig. 9. Influence of hot deformation on the microstructural phases of a pearlite reduced high-strength steel after simulation using a hot forming dilatometer

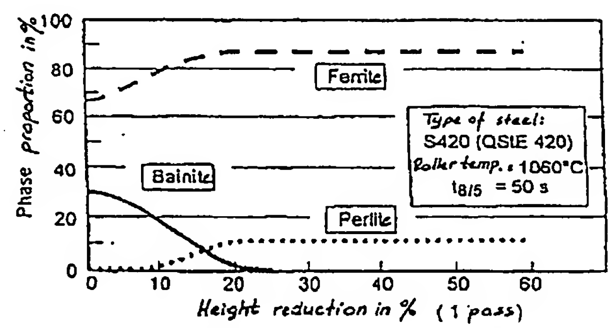


Fig. 10. Results of a numerical simulation of in-line hot rolling of an as-cast steel strip